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**DESIGN POINT CHARACTERISTICS OF A 15-TO-80 kW_e
NUCLEAR-REACTOR BRAYTON-CYCLE POWER SYSTEM**

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ABSTRACT

A study of a 15-to-80 kW_e nuclear-reactor-powered Brayton-cycle power system is presented. The system has a design turbine inlet temperature of $1150^\circ F$ based on the use of a zirconium-hydride reactor but is also required to be capable of operation at turbine inlet temperatures up to $1600^\circ F$ with an advanced reactor. Considerations involved in the selection of cycle parameters, working fluid, pressure level, and turbo-machinery rotational speed are discussed. Size and weight estimates and predicted design-point performance and required radiator area are presented.

NASA-LEWIS AS PART OF its Brayton-cycle space power system technology program has been pursuing the development of power conversion equipment for use with a nuclear-reactor heat-source. Contracts were let in 1969 to obtain a definition of optimum system parameters and preliminary designs of the turbine-alternator-compressor (TAC) assembly and the gas-loop heat exchangers and ducting (HXDA). The contractual effort was based on an in-house study of power conversion equipment producing 40 to 160 kilowatts of gross alternator power for use with an advanced $2200^\circ R$ nuclear-reactor (1)*.

With the cancellation of the SNAP-8 mercury Rankine program in 1970, greater emphasis was placed on the use of a Brayton power conversion module with the zirconium-hydride reactor. A Brayton power system capable of producing tens of kilowatts was also a more immediate need. A conversion system net power range of 15 to 80 kW_e was selected as more appropriate for near-future space power needs and as more closely matched to the zirconium-hydride reactor power level. A mid-range design point of 60 kW_e system output was selected to improve performance in the low-power range and also because two modules operating at 60 kW_e accommodate the 600 kW_{TH} reactor design power. System output power includes the housekeeping electrical needs required for controls and pumps but neglects user-power-conditioning needs.

The Lewis Research Center is presently conducting contractor programs for the fabrication of the TAC and HXDA for a 15-to-80 kW_e power conversion module. The components and ducting will be sized for 60 kW_e operation at a turbine inlet temperature of $1150^\circ F$ corresponding to a $1200^\circ F$ reactor outlet temperature. To allow for operation up to 80 kW_e with an advanced reactor or isotope heat source, the components, with the exception of the heat source heat exchanger, are mechanically and structurally designed for 80 kW_e operation at a turbine inlet temperature of $1600^\circ F$.

These components will form the core of a power conversion module to be performance tested at turbine inlet temperatures of 1150° and $1600^\circ F$. Initially, an electric heater will be used to simulate the heat-source heat exchanger. Therefore, the heat-source heat exchanger which is part of the HXDA will not be fabricated under

*Numbers in parentheses designate References at end of paper.

the present program. At a later date, with the addition of the heat-source heat exchanger a complete power conversion module will be operated with the zirconium-hydride reactor as part of the Combined System Test in the Space Power Facility.

This paper presents the results of the system definition program. Considerations involved in the selection of cycle parameters, working fluid, pressure level, and turbomachinery rotational speed are discussed. Module size and system weight estimates, predicted design point performance, and radiator area requirements are presented.

SYSTEM DESCRIPTION

A schematic diagram of the power system is presented in Fig. 1. The power conversion module, as shown, includes the turbine-alternator-compressor unit (TAC) and the heat exchanger and ducting assembly (HXDA).

TURBINE-ALTERNATOR-COMPRESSOR (TAC) - The TAC includes a radial turbine and compressor and a Lundell-type alternator. All three components are mounted on a common shaft supported by gas bearings.

To conform to the anticipated space station power requirements (2) an alternator frequency of 400 hertz was selected.

HEAT EXCHANGER AND DUCTING ASSEMBLY (HXDA) - The heat exchanger assembly includes the recuperator, waste heat exchanger, heat-source heat exchanger, and all gas-loop ducting. The recuperator is a gas-to-gas, plate and fin, counterflow unit. The waste heat exchanger is a gas-to-organic liquid, plate and fin, cross-counter flow unit. The waste heat exchanger has redundant liquid-coolant passages with only one set of passages being used at any time. The NaK-to-gas heat source heat exchanger is a finned-tubular cross-counterflow unit.

HEAT REJECTION SUBSYSTEM - Separate cooling loops are used for cycle waste heat rejection and alternator-electronic cooling. In this way the electrical cooling subsystem is isolated and independent from changes in compressor or turbine inlet temperature. The same organic liquid is used as coolant in both loops.

HEAT SOURCE SUBSYSTEM - The zirconium-hydride reactor and NaK-to-NaK intermediate heat exchanger are the major components in the heat source subsystem. The intermediate NaK heat exchanger outlet temperature is 1166°F with a temperature rise of 131°F .

SYSTEM PARAMETER SELECTION

The parameter values considered during the initial optimization program (3, 4, 5) are presented in Table 1. The selected values are underlined. Components were sized and analyzed at both 1150°F and 1600°F conditions but module power level was held constant at 160 kW_e .

Much of the initial optimization program for the higher power module is also valid for the present system. The following discussion presents the considerations related to selection of the set of reference design parameters for the 15 to 80 kW_e system.

MOLECULAR WEIGHT AND ROTATIONAL SPEED - A helium-xenon mixture working fluid with a molecular weight of 39.94 and 83.8 was considered. Although a gas mixture was assumed for improved heat transfer properties (6), molecular weights corresponding to argon and krypton were selected so that preliminary component testing could be conducted with the single gas.

The gas mixture with a molecular weight of 39.94 was selected as the working fluid because of lower alternator windage losses and lighter weight heat-transfer components.

Initially, two turbomachinery rotational speeds were considered. The emphasis on 400 hertz alternator output resulted in selection of 24,000 rpm. Aside from the alternator frequency requirement, high alternator stresses and windage losses made the higher speed a poor choice for the 160 kW_e machine.

RECUPERATOR EFFECTIVENESS AND SYSTEM LOSS PRESSURE RATIO - The results of the effectiveness and loss pressure ratio analysis are presented in Fig. 2. The loss pressure ratio is the fraction of the compressor pressure ratio allotted to the turbine or one minus the HXDA pressure loss ratio. Relative heat transfer component weight (HXDA and radiator) and relative radiator area are presented as a function of loss pressure ratio for the two values of recuperator effectiveness. Both area and weight are normalized to unity at an effectiveness of 0.925 and a loss pressure ratio of 0.96. A radiator weight of one pound per square foot of area has been assumed. The waste heat exchanger effectiveness was 0.95 and the capacity rate ratio (gas capacity rate divided by liquid capacity rate) was 0.90 in all cases.

The loss pressure ratio has a significant effect on both cycle efficiency and HXDA weight and size. The weight curves illustrate this combined effect. As loss pressure ratio increases,

radiator weight decreases because of increased cycle efficiency until a minimum total weight occurs when increasing HXDA weight dominates. Minimum weight occurs at a loss pressure ratio slightly more than 0.96 for both values of effectiveness.

For conservatism, a value of 0.96 was used for performance predictions while an HXDA pressure drop ratio of 3 percent, rather than 4 percent, has been specified for design.

A recuperator effectiveness of 0.925 has been selected as the design value because of the 8 percent weight savings with a radiator area increase of only 3 percent. It was also felt that designing for higher values of loss pressure ratio resulted in greater improvements in system performance than increased effectiveness.

CYCLE TEMPERATURE RATIO AND COMPRESSOR PRESSURE RATIO - Cycle performance is reflected in cycle efficiency (η_{cy}) and required specific prime radiator area (A_R/P_{SH}). Gross shaft power (P_{SH}) is the difference between turbine and compressor work. Cycle efficiency is the ratio of gross shaft power to net thermal input power. Prime radiator area assumes a surface effectiveness of unity (no fin). The cycle performance characteristics for the set of reference parameters are presented in Fig. 3. The performance curve is the envelope of individual constant cycle temperature ratio (compressor inlet temperature divided by turbine inlet temperature) curves with compressor pressure ratio as the variable. These individual curves are shown for cycle temperature ratios of 0.34, 0.36, 0.38, and 0.40. The minimum area of 25 ft²/kW occurs at a cycle temperature ratio of 0.46 and an efficiency of 0.18.

Design cycle temperature ratio is selected to give a reasonable trade-off between specific prime radiator area and cycle efficiency based on the performance requirements of a particular mission. Depending upon mission requirements, a value of cycle temperature ratio within the range of 0.46 and 0.36 might be selected. This range represents radiator areas from minimum to about 50 percent above minimum. A cycle temperature ratio of 0.38, corresponding to a compressor inlet temperature of 152° F, representing the middle of the area range, is selected as the design value for this system. The corresponding specific prime radiator area of 32.1 ft²/kW is approximately 30 percent above minimum.

The flexibility of a Brayton system has been demonstrated in the operation of the 2-15 kW test system over a range of cycle temperature

ratios (7). To meet a particular mission requirement a fixed conversion system can operate efficiently over a range of cycle temperature ratios by varying compressor inlet temperature through changes in radiator area. Reference 8 covers in detail the predicted "off-design" performance of the 15-80 kW_e Brayton system.

At the selected cycle temperature ratio of 0.38 a compressor pressure ratio of 1.8 corresponds to the tangency point of the performance envelope. The corresponding cycle efficiency is 0.292 with a specific radiator area of 32.1 ft²/kW.

COMPRESSOR INLET PRESSURE - Having selected all other system parameters, the system pressure level can be determined by selecting a specific speed in the range of good turbomachinery performance. A turbine specific speed of 80 is generally considered indicative of near optimum efficiency (9). At this turbine specific speed, the corresponding compressor specific speed is 90 and the compressor inlet pressure is 35 psi.

The results of an investigation into the effect of pressure level on HXDA size and weight performed as part of the contract effort (5) indicated that a significant reduction in conversion module size and weight could be achieved by increasing pressure level through a reduction in turbomachinery specific speed.

Compressor inlet pressure can be increased to 70 psi by reducing turbine specific speed to 62 and compressor specific speed to 70. Reference 9 indicates that some reduction in efficiency occurs at specific speeds outside the optimum range; however, recent work with the 2-15 kW_e Brayton turbine (10) has found these efficiency effects can be minimized through proper design techniques. For conservatism, a 0.01 penalty was assumed reducing compressor efficiency to 0.83 and turbine efficiency to 0.90. This reduced turbomachinery efficiency is reflected in cycle performance by increasing area and reducing efficiency at the same cycle temperature ratio as shown in Fig. 4. At a temperature ratio of 0.38 and a compressor pressure ratio of 1.8, the reduced efficiency curve is 4.5 percent less efficient and requires 6.5 percent more radiator area.

The effect on HXDA and radiator weight and radiator area is shown in Table 2. The reduction in specific speed, by increasing loop pressure reduces total heat transfer component weight (including radiator) by 11 percent with a 6.5 percent radiator area penalty.

The alternator windage loss is shown in

Table 3 at design power of 60 kWe and maximum power of 80 kWe for the two specific speeds. At a specific speed of 62, the windage loss is approximately 6 percent of gross alternator output over the power range. The increased windage loss at the lower specific speed will be reflected in increased auxiliary radiator area and alternator cooling load. Although alternator windage is a significant loss, it is approximately the same percentage of gross alternator power as the windage loss calculated for the 160 kWe alternator (3, 4).

For reduced power conversion system weight and volume, a turbine specific speed of 62 has been selected for design. The complete list of selected design parameters is presented in Table 4.

POWER CONVERSION MODULE LAYOUT

Heat exchangers were sized for design conditions as part of the HXDA preliminary design program (11). The integration of the HXDA and TAC is presented in Fig. 5. The 60 kWe TAC dimensions were estimated by scaling from the 160 kWe TAC presented in Refs. 3 and 4. The HXDA is shown in a close-coupled arrangement with the heat-source and waste heat exchangers matching the discharge faces of the recuperator. The overall length of the package is 96 inches, the height is 88 inches and the width is 42 inches.

WEIGHT AND PERFORMANCE SUMMARY

Estimated system weight is presented in Table 5. The HXDA and frame weights have been determined by AiResearch (11). The remaining weights have been estimated by scaling from 2-15 kWe Brayton system components and zirconium-hydride reactor system studies. The radiator weight is assumed to be one pound per square foot of area. Radiator area and weight include an allowance for alternator and electrical cooling in addition to cycle waste heat rejection requirements. The system weight is 12,360 lbs including 4160 lbs for the reactor subsystem, 3900 lbs for the power conversion module and 4300 lbs for the heat rejection subsystem. The weight estimates do not include such mission dependent items as reactor shielding, storage batteries, transmission lines, user power conditioning equipment, and radiator structure.

A summary of estimated system power losses is presented in Table 6. Based on these loss

estimates, system performance at design power of 60 kWe was determined and the results are summarized in Table 7. Gross alternator power measured at the alternator terminals is 70 kWe .

At design net system power of 60 kWe , net efficiency is approximately 0.20 with an unshielded system specific weight of 206 lbs/ kWe and a required radiator area of 65 ft^2/kWe . Operating a single-module system at peak power of 80 kWe reduces system specific weight to 172 lbs/ kWe with approximately the same specific radiator area.

System output power can be increased beyond 80 kWe by using multiple power conversion modules with the zirconium-hydride reactor. Two modules each producing 60 kWe for a net system output of 120 kWe required 610 kW thermal power, approximately the reactor design power. System specific weight is 171 lbs/ kWe while specific radiator area remains at 65 ft^2/kWe . Assuming growth capability of the reactor to 1200 kW thermal power, three power conversion modules operating at peak power can produce a system output of 240 kWe with a specific weight of 137 lbs/ kWe .

CONCLUDING REMARKS

The set of reference design parameters for the 15-80 kWe Brayton power conversion module for use with the zirconium-hydride reactor has been selected. The following list presents the major design parameters selected:

Turbine inlet temperature, $^{\circ}F$	1150
Compressor inlet temperature, $^{\circ}F$	152
Working fluid molecular weight	39.94
Rotational speed, rpm	24,000
Compressor pressure ratio	1.8
Turbine specific speed	62
System loss pressure ratio	0.96
Recuperator effectiveness	0.925

At design conditions, the power system produces an estimated net system output power of 60 kWe with a reactor power of 305 kWe for an overall efficiency of approximately 0.20. Estimated system specific weight is 206 lbs/ kWe with a required radiator area of 65 ft^2/kWe .

Operating a single module at increased power or using multiple power conversion modules with the reactor can significantly reduce system specific weight with approximately constant specific radiator area.

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Table 1. - Initial Range of Parameters Investigated

Turbine inlet temperature, °F . . .	1150, 1600
Helium-xenon molecular weight . . .	39.94, 83.8
Rotational speed, rpm	24,000, 36,000
Loss pressure ratio	0.92, 0.94, 0.96
Recuperator effectiveness	0.925, 0.950

Table 2 - Specific Speed Effect on Heat Transfer Component Weight and Radiator Area

Turbine Specific Speed	80	62
Radiator Area, ft ²	3200	3410
HXDA Weight, lbs	2730	1880
Radiator Weight, lbs	3200	3410
Total Weight, lbs	5930	5290

Table 3 - Specific Speed Effect on Alternator Windage

Turbine Specific Speed	80		62	
Net System Power, kWe	60	80	60	80
Estimated Windage Loss, kWt	2.2	3.0	4.3	6.0

Table 4 - Summary of Design Parameters

Power range, kW _e	15-80
Design power-Gross Alternator Output, kW _e	70
Turbine inlet temperature, °F	1150*
Compressor inlet temperature, °F	152
Loss pressure ratio	0.96
Recuperator effectiveness	0.925
Heat source heat exchanger effectiveness	0.956
Waste heat exchanger effectiveness	0.95
Compressor efficiency	0.83
Turbine efficiency	0.90
Compressor pressure ratio	1.8
Compressor inlet pressure, psi	70
Rotational speed, rpm	24,000
Working fluid	Helium-xenon gas mixture
Molecular weight	39.94
Flow rate, lb/sec	7.1
Design life, yrs	10
Alternator frequency, hertz	400

*Components, except for heat-source heat exchanger, must be capable of long-term operation in a 1600° F system producing 100 kW_e.

Table 5 - System Weight Summary

Reactor and Intermediate Loops	
Reactor	1,830
NaK-to-NaK heat exchanger	140
Pumps	1,100
Piping, structure, inventory, accumulators	<u>1,090</u>
	4,160 lbs
Power Conversion, Module	
HXDA	1,880
TAC	800
Frame	120
Controls, electrical packages	1,000
GMS	<u>100</u>
	3,900 lbs
Heat Rejection Loops	
Radiators	3,850
Pumps	100
Piping, accumulators, inventory	<u>350</u>
	<u>4,300</u> lbs
SYSTEM TOTAL	12,360 lbs

Table 6 - Summary of Estimated Losses

Pumping power, kW _e	7.3
Electrical housekeeping power, kW _e	2.7
Bearing Loss, kW _T	2.5
Power conversion module thermal loss, kW _T	3.0
Alternator windage loss, kW _T	4.3
Alternator electromagnetic efficiency	0.93

Table 7 - 1150° F Design Performance Summary

Gross alternator power, kW _e	70
Net system power, kW _e	60
Reactor thermal power, kW _T	305
Net system efficiency	0.20
System specific weight, lbs/kW _e	206
Specific radiator area, ft ² /kW _e	65

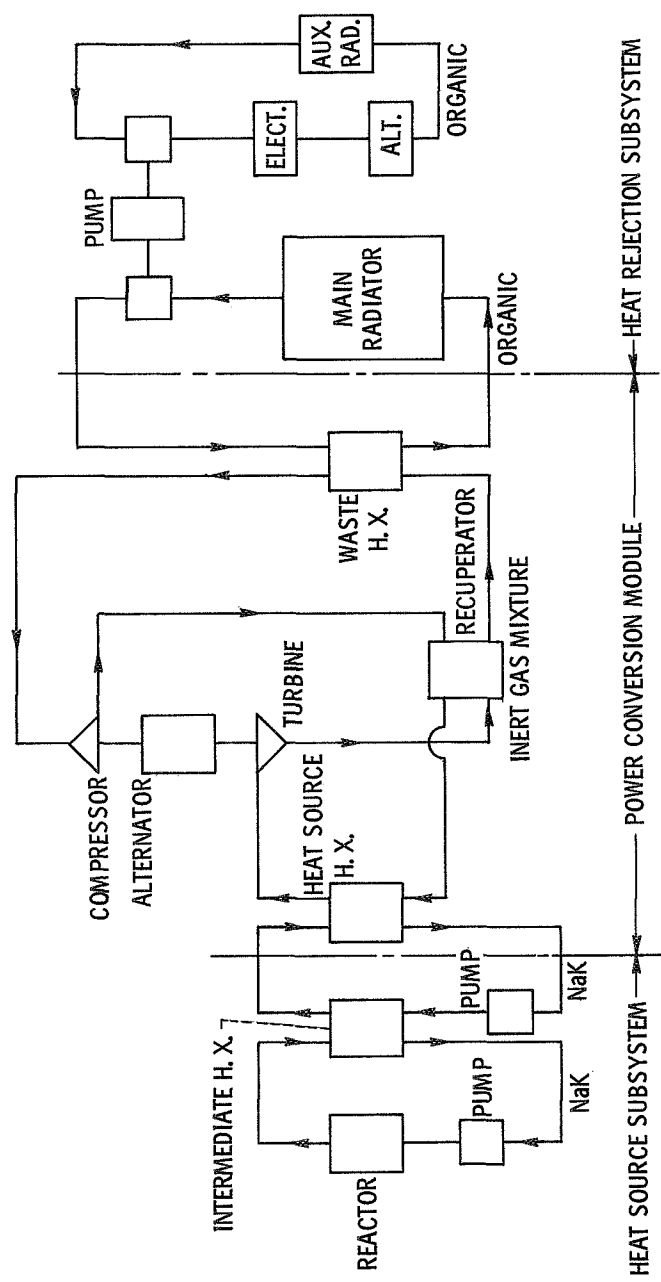


Figure 1. - Reactor Brayton system schematic.

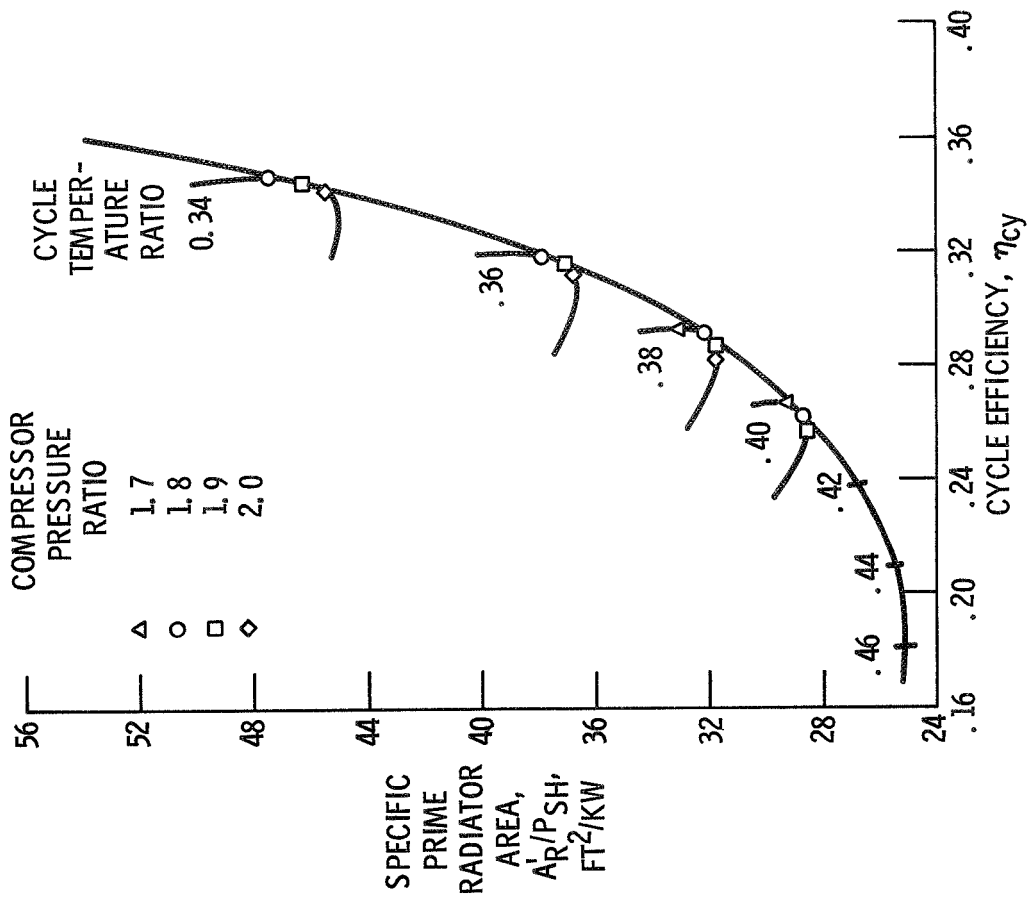


Figure 3. - Cycle performance characteristics for a turbine inlet temperature of 1150° F, compressor efficiency of 0.91, loss pressure ratio of 0.96, turbine efficiency of 0.91, loss 0.925, radiator sink temperature of 10° F, and radiator surface emittance of 0.88.

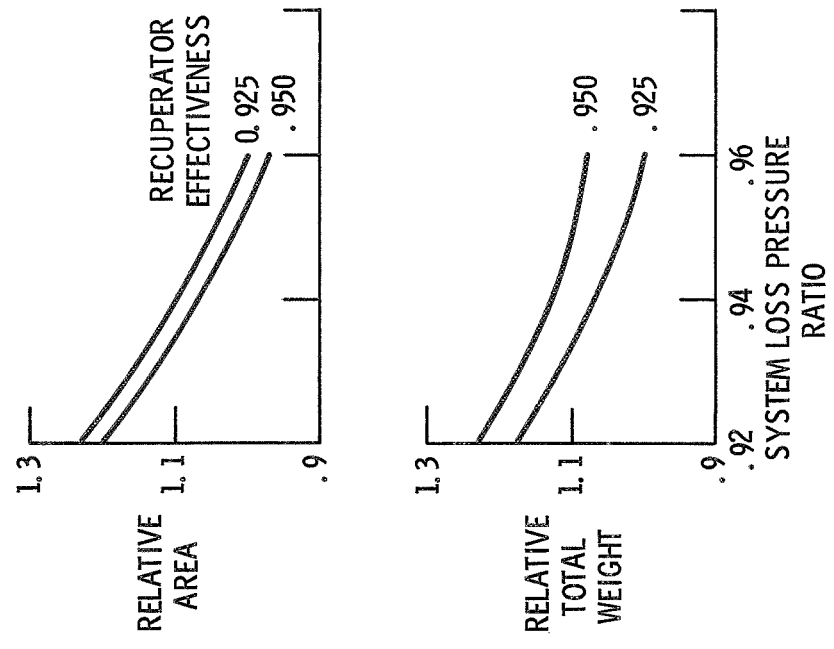


Figure 2. - System loss pressure ratio and recuperator effectiveness effects on heat transfer component weight and radiator area for 1150° F design conditions.

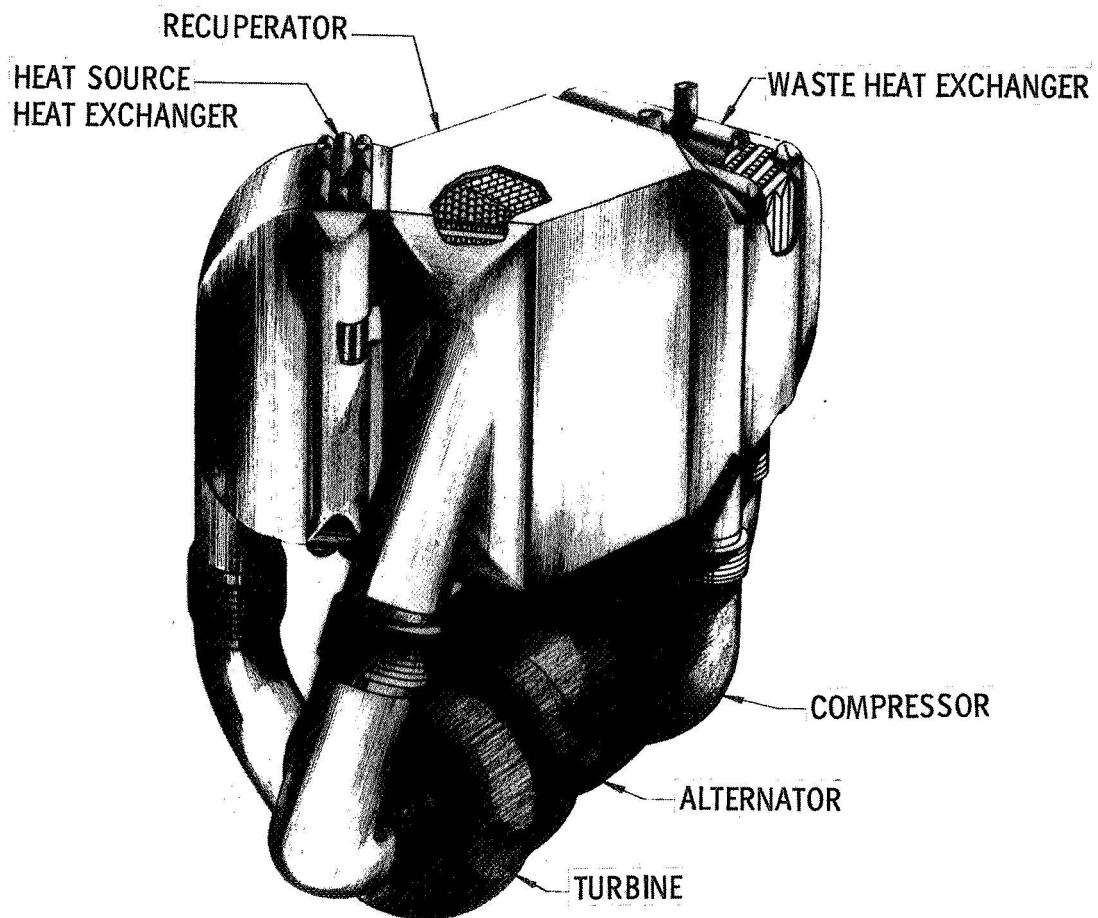


Figure 5. - Power conversion module layout.